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Abstract

The most critical events of the Galileo mission occur on Jupiter arrival day, December 7, 1995. In chronological order, these one-time events are: a 1,000 krn altitude flyby of the innermost Galilean satellite 10, the 75-minute Atmospheric Entry Probe mission, and the Orbiter's Jupiter Orbit Insertion (JOI) maneuver. In addition, extensive, unique Orbiter science observations are planned because this is the only time Galileo will encounter Io, fly through the Io torus, and will be so close to Jupiter- three times closer than at any of the perijove passes in the orbital mission. All of these events occur in what will be by far the most intense radiation environment Galileo will ever see.

The focus of this Paper is the extraordinary preparations being made to maximize the reliability of the most critical events in order to ensure a successful Probe mission and Orbit Insertion while also gathering unique arrival clay Orbiter science.

The Paper also provides a mission status report inducting the return of the asteroid Ida data and the Galileo direct line-of-sight observations of Comet Shoemaker-] .evy fragments impacting Jupiter in July 1994.

1. Introduction

In just less than fourteen months, on December 7, 1995, Galileo will arrive at Jupiter completing its over six-year circuitous interplanetary journey. Even though there is a bit more than a year to go, Galileo has already traveled over 90 percent of its interplanetary path length as indicated in Figure 1.

An overview of flight activities performed this calendar year and those required between now and arrival is provided in Figure 2. These activities and

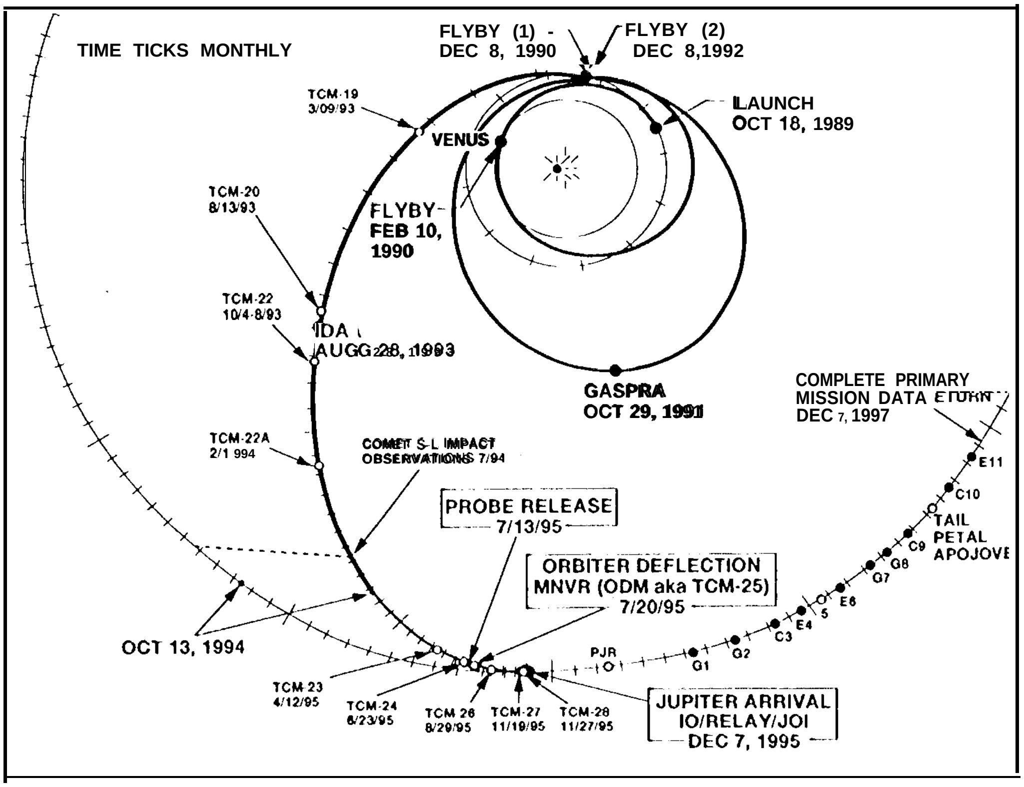

Figure 1. The Galileo Trajectory

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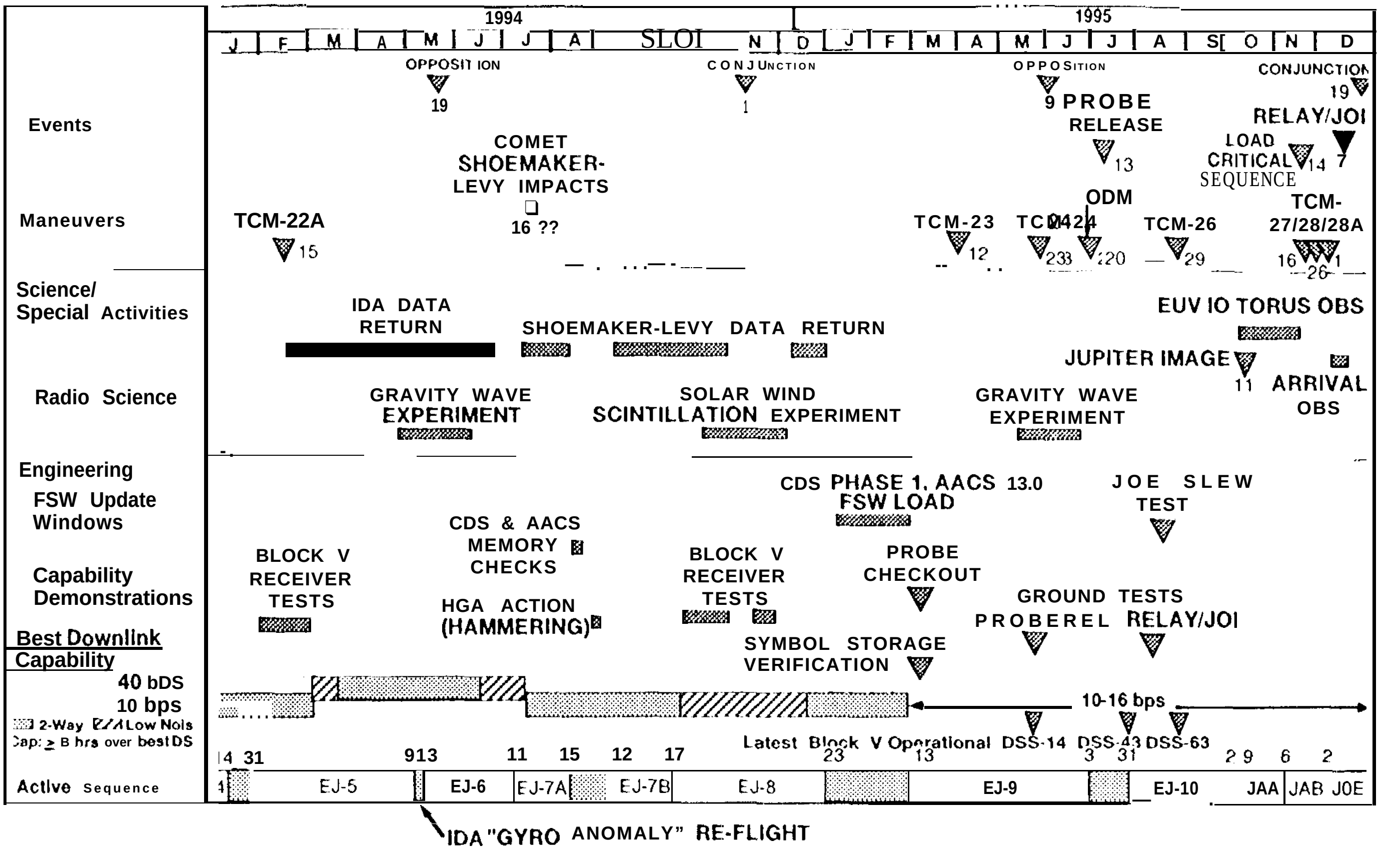


Figure 2. Mission Overview Approaching Jupiter

preparations for them are the subject of this Paper. All high-priority asteroid Ida data was returned in spite of some new challenges. 'J'he most delightful challenge stemmed from the first-ever discovery of an asteroid satellite. In July, Galileo performed observations of Comet Shoemaker/l, evy-9 (SL-9) fragment impacts on Jupiter. Due to its unique vantage point in space, only Galileo's "telescopes" could see the impact region when the impacts were occurring. Some excellent impact observations have already been played back to Earth and the balance of the feasible return will be completed by early 1995.

The Atmospheric Entry Probe will be checked out in March 1995, following the loading of the new arrival phase flight software in the Orbiter (Ref. 1). The Orbiter is now scheduled to release the Probe on July 13th. Seven days later, *on* July 20th, the Orbiter 400N main engine will be used for the first time to deflect the Orbiter to its Jupiter aim point. Five months later, both vehicles arrive at Jupiter as illustrated in Figure 3. The Orbiter performs a 1,000 km altitude gravity-assist flyby of Io and then subsequently overflys the descending Probe (Fig. 4a) to gather the Probe data via the Relay Link for 75-rein. About an hour after the Relay, the 400N engine will burn for nearly an hour to place Galileo into Jupiter orbit.

The Orbiter's two-year primary mission satellite-gravity-assist orbital tour of the Jupiter System (Ref. 2) is illustrated in Figure 4b. Figure 1 shows when each Orbiter perijove pass/satellite encounter occurs and the corresponding position of Jupiter for each. References 1 through 4 provide comprehensive descriptions of the Galileo mission, spacecraft, and science payload. 'l'he spacecraft health and performance continue to be excellent. All the new capabilities in development to perform the mission with the Low Gain Antenna (LGA) (Ref. 1) are on schedule and will meet and in many cases exceed original expectation .

2. Mission Operations - Selected Topics

The most significant operations activities during the past year were Trajectory Correction Maneuver ('l'CM) -22, the Ida data retrieval, and the SL-9 observations. The Ida and SL-9 activities are described elsewhere in this paper.

only two TCMS were performed this past year (See Fig. 5). TCM-22 in early October 1993 imparted 38.6 n]/see, the largest maneuver ever required of the ION thrusters. It was the first maneuver to actually target Galileo to the Jupiter aim point.

The maneuver was divided into five portions each controlled by a separate mini-sequence. Starting

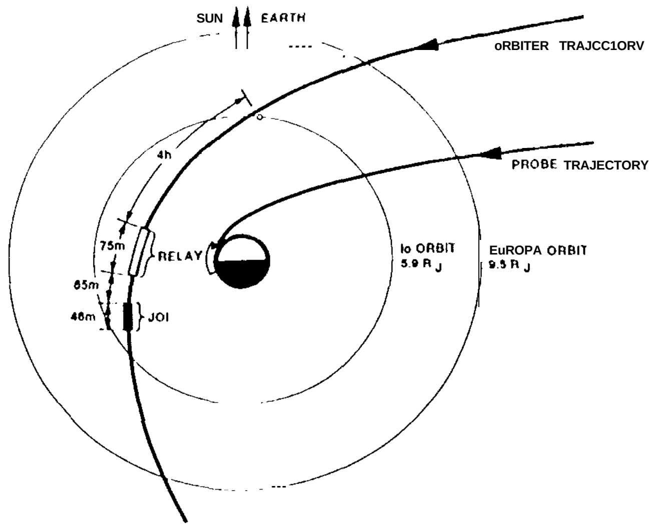


Figure **3.** *Arrival Geometry*

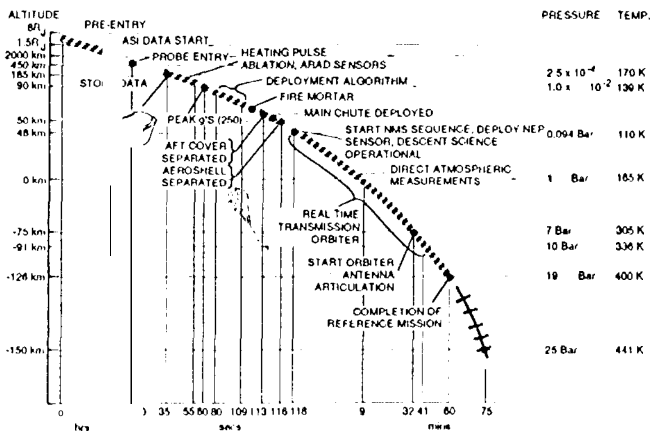


Figure 4cr. *Probe Entry / Descent Events*

with Portion 2, each mini-sequence was transmitted to the spacecraft after the mini-sequence for the preceding portion was completed. On October 1, 1993, the spacecraft was commanded to the maneuver attitude. TCM-22 started on October 4, 1993 at 10:25 UTC. The last portion was completed on October 9, 1993 at 04:22 UTC. Each portion included 8 lateral segments averaging approximately 962 pulsing revolutions - the L thrusters were used with each thruster firing once each revolution. TCM-22 used 35.2 kg of propellant.

TCM-22A, one of the smallest maneuvers yet, was performed on February 15, 1994 to correct the TCM-22 execution errors. It was a single portion maneuver consisting of one lateral segment with 6 pulsing revolutions using the 1, thrusters and one axial segment with 36 pulsing revolutions using the lllA thruster.

The Flight Team was on line for more than 12 hours each maneuver day including for TCM-22 the

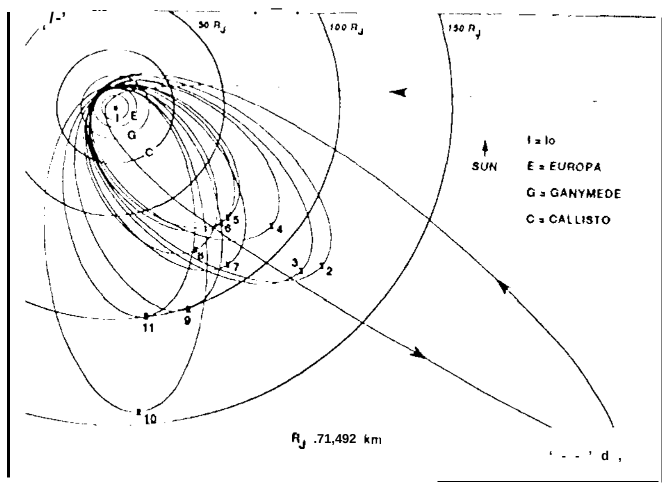


Figure 4b. Orbital Tour of the Jupiter System

daily uplink of the sequence for the next portion. They did an outstanding job. The performance of the Spacecraft, in general, and the Retropropulsion Module (RPM) in particular was outstanding.

Propellant Margin is the estimate of the usable propellant that will be remaining at the end of the primary mission with 90% probability. Currently, the Propellant Margin is a positive 15.7kg having increased 10.4 kg in the past year. "This improvement is primarily attributed to the following major changes:

(1) Deletion of a previously planned "High Gain Antenna (HGA) cold turn" and another 10 RPM spin-up demonstration
(2) Expansion of the sequence box size which allows post-satellite encounter orbit trim maneuvers to be executed 3 days after closest approach.
(3) Improvements in orbit determination accuracy based upon inclusion of optical navigation data to update satellite ephemeris estimates.
(4) Incorporation of an Io occultation in the tour following the E6 encounter. The Io occultation actually reduced Propellant Margin, but the reduction was more than offset by the other changes.

Over this past year, the commutative count of commands transmitted from the ground to Galileo since launch has doubled to a total of 254,289 commands as of September 1, 1994. Spacecraft activity, however, was less than in past years. Of the 123,399 commands transmitted this year, over 90,000 were used to test every cell in half of the CDS memory and half of the AACS memory --- the halves that are not in regular use. Every cell was found functional. The regular use of the prime halves and these tests give high confidence that all memory will be functional for the new flight software required at Jupiter (Ref. 1). This year's record commanding activity was accomplished without a flaw.

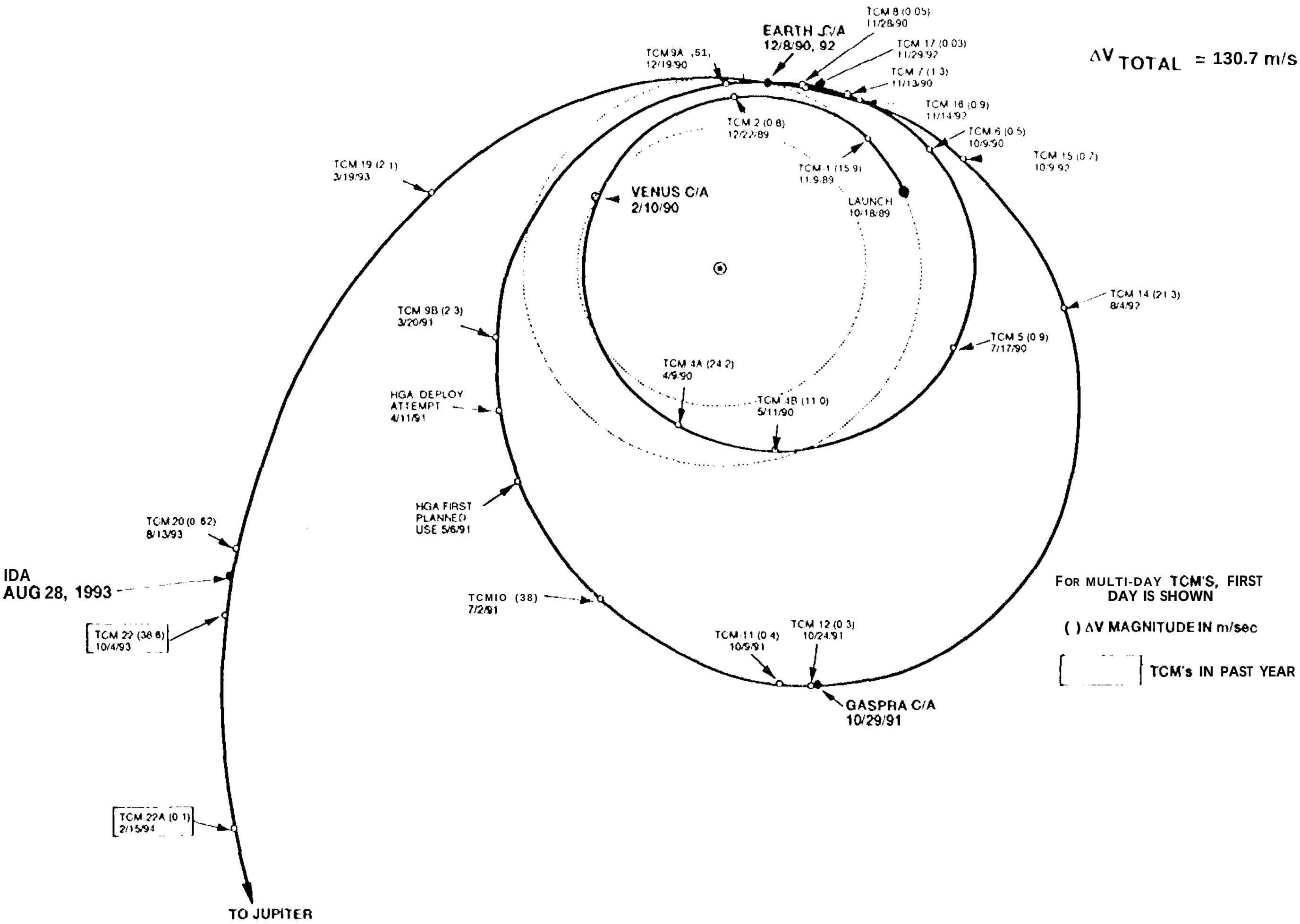


Figure 5. Trajectory Correction Maneuvers to Date

3. Ida Data Return

The playback of the Ida science data recorded on the tape recorder during the August 28, 1993 encounter was a real challenge. The following issues were involved:

- Uncertainty in the relative location of Ida and Galileo Spacecraft,
- Uncertainty in Spacecraft attitude/ instrument pointing,
- Downlink data rate/data mode constraints resulting from the HGA anomaly and S/C-Earth distance,
- Uncertainty in precise positioning of tape recorder tape,
- Tape recorder consumables management , and
- Ground tracking station contention/availability.

The data return plans and resulting spacecraft sequences were necessarily complex. Because of some unforeseen events these plans/sequences were changed frequently. Ultimately, better than 98% of the high priority data was returned.

3.1 Playback Opportunities

At the outset, it was decided to return Ida data only when the telecommunications downlink supported 40 bps telemetry rate. The resulting two periods for data playback are shown on Figure 6. These periods were dictated by the unavailability of the HGA and the relative distance between the Earth

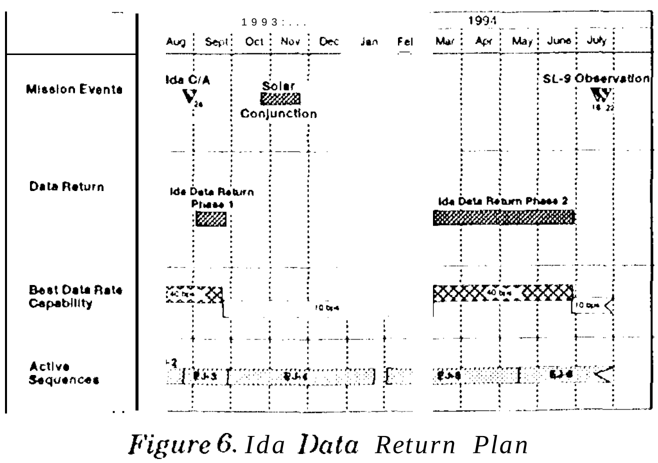


Figure 6. Ida Data Return Plan

anti the Spacecraft. This relationship is shown on Figure 7. Approximately 1,300 hours of tracking station time, spread over the two playback opportunities, was required to return the Ida data.

3.2 Design Concept

The playback of Ida data was accomplished by spacecraft stored sequence control. Dependence on real time commanding was to be minimized. Background sequences controlled the operation of the spacecraft. In addition to other functions, each background sequence included a preview of the data on the tape recorder (Jailbar Search) so that the high priority data could be located for later return. On the basis of the jailbar search data, mini-sequences were developed (Reserve Box Sequences-RBS's). The RBS's specifically control the positioning of the tape within the tape recorder so that the desired data would be transferred from the tape recorder to the central computer and then to the ground (See Fig. 8). Commands from the background and the mini-sequences had to be integrated and issued by the spacecraft in time order. 'l'he concept of integrating background sequences and tape positioning mini-sequences provided sufficient flexibility to accommodate the issues identified earlier without an overwhelming level of work.

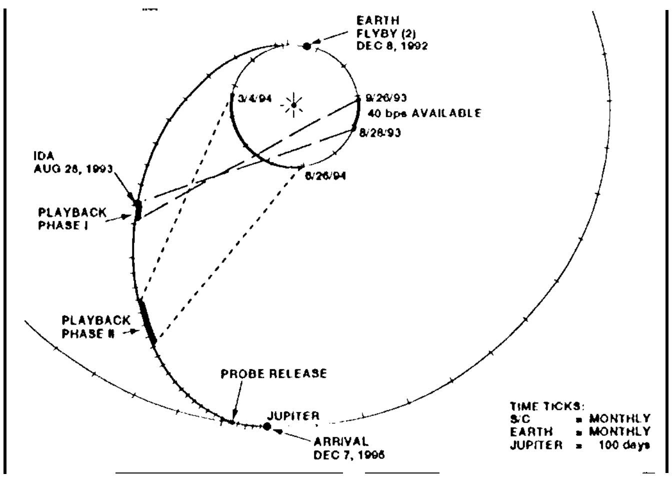


Figure 7. Ida Playback

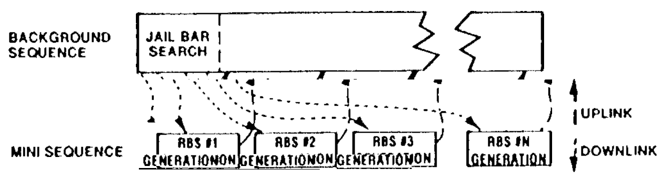


Figure 8. Sequence I Mini Sequence Interdependency

3.3 Phase One Return

Playback Phase 1 started on September 3, 1993. Return of the high resolution Solid State imaging (SSI) instrument data was the objective of I'base 1. On September 5, 1993, the tracking station at Canberra, Australia experienced a power distribution transformer failure. 'J'he I'base 1 Playback had been designed to use the 70m tracking stations at Goldstone and Canberra (Canberra was the best station because it could "see" Galileo for nearly ten hours each pass). Since the playback was controlled by the background sequence already being executed by the spacecraft, the loss of a station could not be easily accommodated. The tracking station at Madrid was reassigned to Galileo initiating the complete replanning of the data retrieval to take advantage of the new tracking station allocation and the loss of Canberra, 'l'his effort resulted in a new set of mini-sequences to control the transfer of data from the tape recorder to the central computer. Fortunately, the loss of Canberra support occurred after the Jailbar search of all the high resolution imaging frames. All the information required for the design of required new mini-sequences was available, This relationship is shown in Figure 8. The Canberra transformer failure also occurred after the Reserve Box Sequence (RBS #/l), which was to have controlled the tape positioning for the first part of Ida playback Phase 1, had been transmitted to the Spacecraft and had been active. RBS #1 had to be canceled. A total of 6 mini-sequences were generated and integrated with the background sequence. During the Phase 1, Ida data was returned for a total of 249 hours at 40 bps. On September 22, 1993, the Ida high resolution image was released to the public. It was presented at the 44th Congress of the IAF (Ref. 1).

3.4 Phase Two Playback

The second I'base of the Ida data playback started on February 16, 1994 with the Jailbar search of all the remaining high priority Ida data. The EJ-5 sequence controlled the jailbar search, the copying of data from the tape recorder to the central computer as well as all other Spacecraft operations during a three month, two week period. Early in the EJ-5 sequence, it was possible to operate at 40bps for brief intervals during selected tracking passes when the Spacecraft was near zenith. The Spacecraft was commanded in real time to 40 bps when that rate was supportable and then commanded back to 10bps. Three of the four jailbar searches were accomplished at 10 bps; the fourth and all the subsequent data return was accomplished at 40 bps. On March 7, 1994 when 40 bps was continuously sustainable, the playback of Ida data was resumed. During I'base 2, the

Project generated 6 RBS's. The EJ-6 sequence, which controlled the remainder of the Ida data playback, was updated shortly before it was uplinked to the spacecraft enabling the pre-planning of all EJ-6 data return and eliminating the need for RBS's i.e., the RBS tape positioning was built into the EJ-6 sequence.

The Ida encounter provided still another challenge. The discovery of Ida's satellite caused the rework of the previously defined priority scheme and a great deal of last minute sequence revision to make sure that all Ida satellite data was played back. This, of course, was just the kind of challenge every member of the Flight Team dreams about. Discovery is, after all, the raison d'être of the Galileo Mission.

Ida's satellite, 1993(243)1, was first detected in the early part of the jailbar search of imaging data on February 17th; it was confirmed in the NIMS chemical map jailbar search data 8 days later. Fortunately, the Flight Team was able to adjust the science data return priorities and to generate necessary mini-sequences that retrieved exactly the desired data from the tape recorder. During Phase 2 of the Ida data replay, 988 hours of tracking was scheduled for Ida data; of those, only eight hours and twenty minutes were lost due to problems at the tracking stations- none of this data was considered by the scientific community to be of high enough priority to preempt data still scheduled for replay.

4. Ida Images

On the facing page is a collection of images of Ida and its satellite, 1993 (243) 1, which were taken by the SS1 instrument.

At the bottom of the page is a single image showing Ida and it's satellite. This was taken from a range of 10,870 kilometers, just, 14 minutes before the Galileo's closest approach to Ida.

The insert is the best image of Ida's satellite. It was taken from a range of 3,900 km just 4 minutes prior to the spacecraft's closest approach to Ida. The satellite is approximately egg shaped, measuring 1.2 x 1.4 x 1.6 km.

The discovery of Ida's satellite was delayed due to delays in data replay. All the data was acquired on August 28, 1993, and placed on the spacecraft tape recorder; but until the data playback resumed in February 1994, there was no hint of the surprise discovery.

In the middle of the page is a collage of images taken during Galileo's approach showing the different faces of Ida as it rotated on its axis. By using the entire collection of images acquired during the encounter of Ida, the size and shape of this very irregular, croissant-shaped body can be determined accurately.

At the very top of the page is an image of the limb of Ida taken 46 seconds after closest approach. It is the highest resolution image of an asteroid surface ever taken showing details at a scale of 25 meters per pixel. Since Ida's exact location was not well known prior to the Galileo flyby, the chances of capturing Ida on the 15 frame mosaic centered around closest approach was estimated to be 50%. Fortunately, this frame did capture part of the sunlit side of Ida.

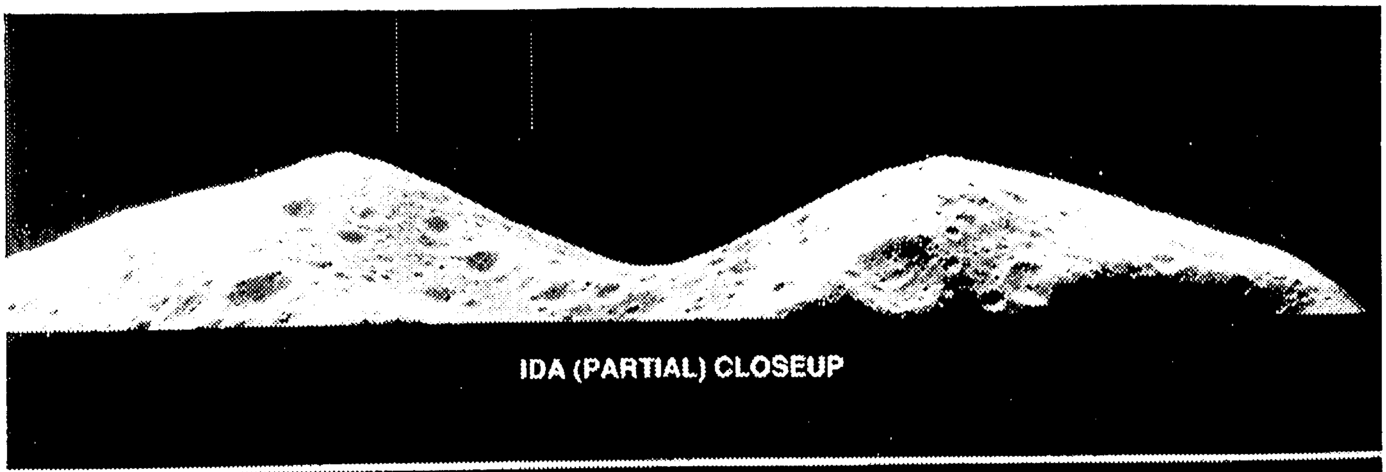
Data from the NIMS, PPR, MAG, as well as, other participating instruments were retrieved and will be used by the science community to develop a comprehensive characterization of Ida and its satellite.

5. Spacecraft Performance

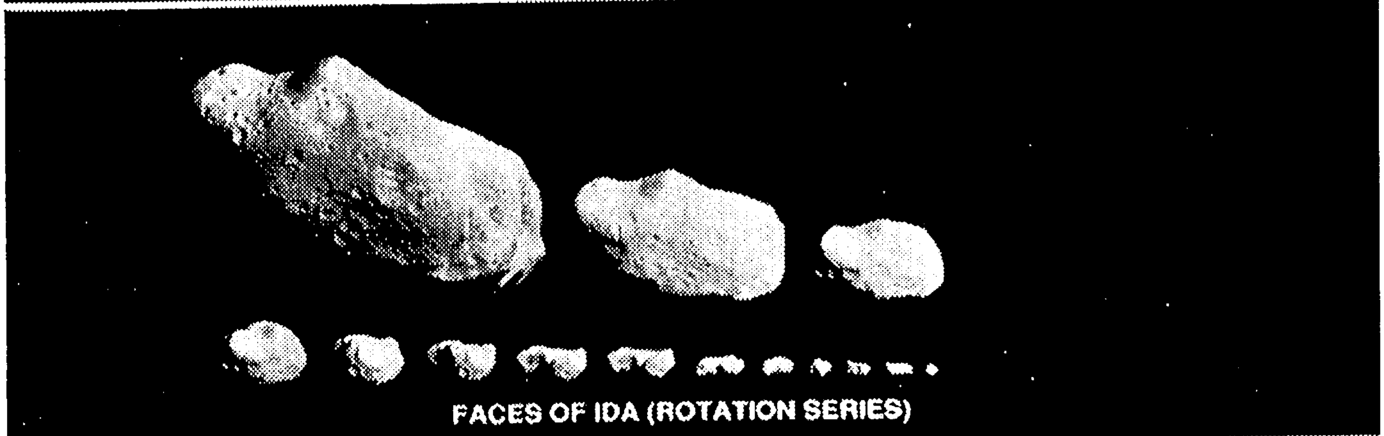
Spacecraft performance continues to be excellent. All Galileo subsystems continue to perform in an exemplary manner. During the past year, two significant thermal-related changes have been made to the electrical heater configuration. A despun electronics structural mounted heater was powered on continuously to protect sensitive despun electronics from experiencing a large temperature excursion and remain within acceptable limits should adjacent electronics become unpowered. The additional heater power raises the thermal environment into the louver range where power dissipation-temperature sensitivity is less. Also, the flash heater on the SS1 radiator plate was turned on to maintain the SS1 detector temperature limits rather than have the SS1 instrument main power on.

Galileo has superbly performed all TCMs, attitude maintenance maneuvers, propulsion maintenance flushing pulses, calibrations, telecommunications tests, and other activities in support of the Ida encounter and data return. In July, the spacecraft flawlessly executed the SL-9 impact observation stored sequence and began early return of some comet fragment impact data; more impact data will be returned through the balance of this year and in January '95. in addition, computer memory checkout tests were successfully performed in August and several special telecommunication characterization tests are schedled for later this year.

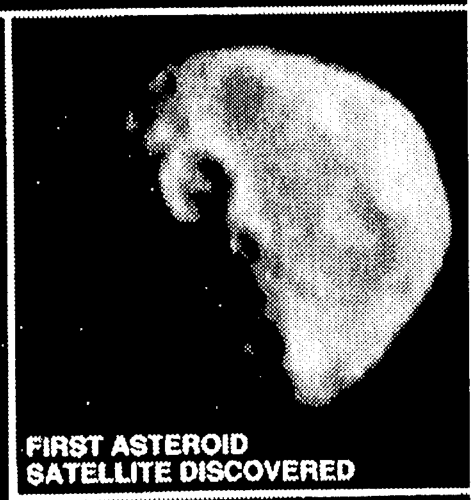
Though spacecraft performance has been excellent, some unpredicted events have occurred. Noteworthy events were the occurrence of a Command and Data Subsystem (CDS) transient bus reset in the all-spin mode, an Attitude and Articulation Control Subsystem (AACS) autonomous inertial-to-cruise mode change, and a significant change on the Direct Current (DC) bus imbalance measurement. None of these unexpected events poses a threat to the spacecraft health. The following paragraphs briefly summarize each of these three notable events in more detail.



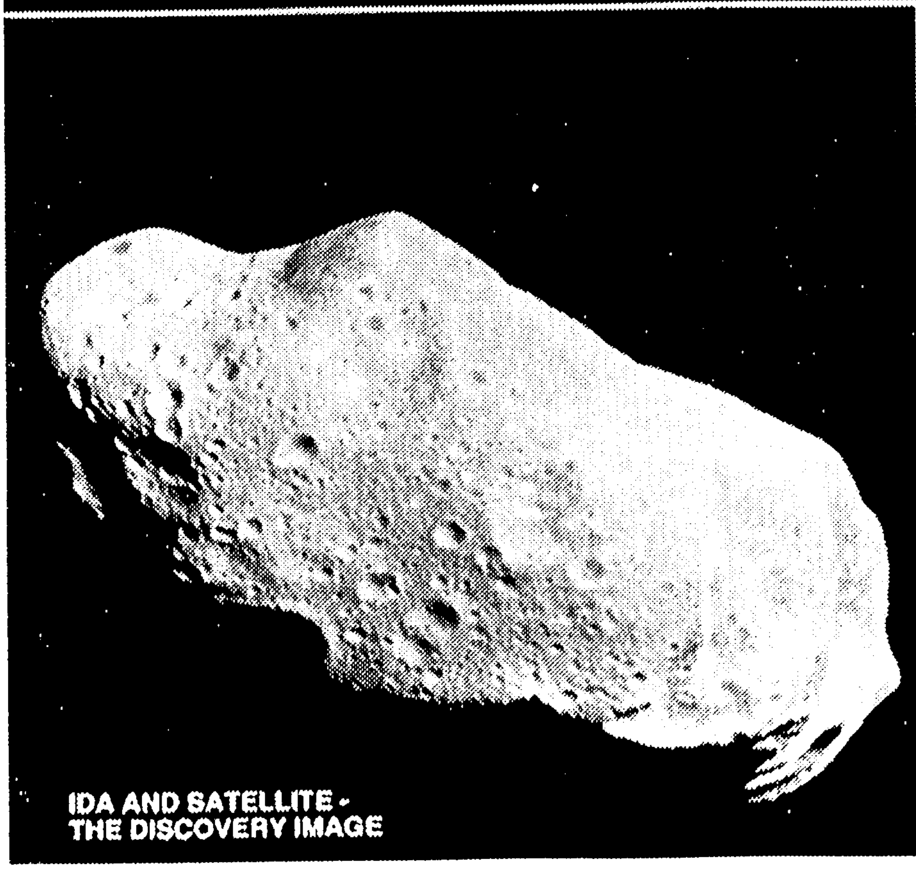
IDA (PARTIAL) CLOSEUP



FACES OF IDA (ROTATION SERIES)



FIRST ASTEROID SATELLITE DISCOVERED



IDA AND SATELLITE - THE DISCOVERY IMAGE

5.1 All-Spin Bus Reset

A CDS spurious transient bus reset occurred on September 24, 1993 in the all-spin mode. This was a major surprise and immediately prompted intensive sophisticated computer analyses efforts to understand the dynamics at the slip ring-brush interface as a function of spacecraft spin mode (all-spin, dual-spin, and quasi all-spin). It had been thought that the absence of significant relative motion between the spacecraft spun and despun sections precluded these bus resets in all-spin mode. The computer modeling revealed that mechanical "dither" motion between the spun and despun sections as small as 30 to 40 micro-radians is enough to cause momentary (1 0-20 microsec) simultaneous brush '(lifting" or brush "heel-toe rocking". This condition in conjunction with existing brush-debris-formed spurious electrical paths in the Spin Bearing Assembly (SBA) can cause bus resets. Furthermore, the analysis indicated that all-spin seems to be the most likely (from a dynamics view) mode for enabling these bus resets. Because transient bus resets are thought to be caused by electrical debris paths in the SBA coupled with momentary, drastically lower brush-ring electrical conductivity (clue to rocking or lifting), the spacecraft is now being operated primarily in the quasi-all-spin mode (relative motion between sections of **0.2** deg/ see). This operating mode minimizes the generation of additional brush debris, ensures adequate bearing lubrication, helps preclude possible slip-ring contamination and is mechanical ly less sensitive to "rocking or lifting." The all-spin and dual-spin operating modes will be used only when required for mission/ spacecraft activities (e. g., remote sensing) until orbital operations. Dual-spin will be primary in orbital operations where the new flight software will automatically recover from resets.

5.2 Gyro Fault Protection Trip

On August 28, 1993, about 5 hours before Ida closest approach, the spacecraft gyros were autonomously powered off via fault protection in response to detection of high rates (outside of preset limits) sensed by both gyros. As a consequence, the Ida encounter was performed in cruise mode rather than the inertial mode (gyros on) which provides better scan platform pointing (see Ref. 1). Despite the slightly degraded scan platform pointing, the encounter was a spectacular success. Because of the low (10 bps) real-time telemetry rates available during the encounter, it was not immediately possible to determine why the gyros were turned off. An extensive test and analysis effort, including testbed simulators and a thorough review of the flight software code and timing, provided no clue to the anomaly. Subsequent tape recorder playback of the Ida data provided some additional information for the anomaly investigation but still no clue. The Ida playback data, however, did provide some important information revealing that unexpected scan platform (where gyros are mounted) motions occurred several times in both control axes as evidenced from higher than expected power consumption and other telemetry data.

Because the anomaly could not be re-created with the test simulators, explained via software analyses, or analyzed via diagnostic flight data; a special flight test was performed in May 1994 using identical portions of the original Ida sequence where the initial anomaly and other slew-related anomalies occurred. The anomaly did not recur during the flight test. It is noted that ever since the Ida anomaly, the AACS gyros, electronics, and scan platform have operated flawlessly with no hint of a problem. At this writing, it has just been determined that a transient error in the cone encoder data word can result in all the anomaly symptoms in a remarkable pathology. The source of such an error is being sought.

5.3 DC Bus imbalance Change

During the past year the AC/DC power bus imbalances continued to fluctuate. 'l'he Alternating Current (AC) imbalance measurement exhibited only minor changes remaining fairly stable near its March 1992 level of 4,5 volts. 'l'he DC bus imbalance measurement, after about 7 months of near-stable operation, exhibited significant changes over a three day period in mid-May 1994, shortly after transition to quasi all-spin. During this period, several other engineering measurements also changed. Changes were observed on the AC bus current, DC bus current, shunt current, CDS +10 volt power supply current, SBA temperature, and the Ultra-Stable Oscillator (USO) oven current. Analyses showed that all the changes can be explained by the clearing of spurious slip-ring brush debris paths in the SBA. Previous ground tests demonstrated that debris paths are cleared with low current levels (50 to 100 mA). 'l'he flight observed current, power, and temperature changes are internally consistent and consistent with ground test data.

5.4 Galileo-Mars Observer Comparison Study

As a consequence of the permanent loss of signal from the Mars Observer (MO) spacecraft, an intensive effort was undertaken by a multi-discipline team to verify that the Galileo spacecraft is not susceptible to the MO type failure modes identified by the failure review process. Based on the NASA, JPL, and Martin Marietta failure reports and JPL audit, l'reject Galileo performed a comparison study covering all the identified MO failure modes, including propulsion, telecommunications, power, etc. The comparison study results and conclusions were independently reviewed by a special board (including several members from the MO failure analysis team) in May 1994. The study concluded that Galileo is not susceptible to MO type failures, there is no reason to change planned operational use, and there are no risk areas that had not been previously accounted for. The Review Board unanimously endorsed the study findings.

6. Shoemaker/Levy-9 (SL-9) Observation Plan

Since the SL-9 impacts occurred on the leading side of Jupiter, but on the back side, beyond the limb, as seen from Earth, Galileo was in the unique position of being able to see the impacts as they occurred, rather than observing the effects several minutes later, as was the case for all Earth-based observations (See Fig. 1).

Normally when designing a science observation, there is little if any uncertainty about the desired time of the observation; the uncertainty is in target ephemeris and instrument pointing accuracy. A common solution to this is to design a mosaic that covers an area large enough to insure that the target is observed. The comet impact observation sequence design problem was effectively the opposite of this- the target (Jupiter) ephemeris was not a factor, and instrument pointing accuracy needed to be considered, but was not a significant issue, but the time of each event was uncertain to tens of minutes. This posed a significant challenge in the design of these sequences, especially in view of the fact that the sequences were very complex and could not be fully updated as the impact time estimates changed. The measurement strategy development faced the additional challenge that temporal scale and intensity of the impact phenomena were generally uncertain by several orders of magnitude. Most all the observation data had to be stored on the tape recorder, which can only hold the data equivalent of about 150 SS1 full frame images. Due to the 10 bps telemetry limitation, only about 5% of the tape can be returned in the time available, Even after the impacts had occurred and were recorded, the impact times still would not be known to better than a few minutes, and maybe more, depending on how much was seen by ground-based observers, so the problem was how to know where on the tape to go to retrieve the data for playback.

Five of the eleven instruments *on* the Galileo spacecraft were deemed suitable for observing the comet impacts. The instruments that make in-situ measurements are not usually suitable for making observations at a distance of 1.6 AU. Four of the five instruments were the remote sensing instruments mounted on the scan platform - SS1, NIMS, PPR, and UVS (See Ref. 4 for instrument description). The fifth was the PWS, included because of the possibility that it could detect radio frequency emissions caused by the impacts. A sixth instrument, the Dust Detector Subsystem (DDS), will watch for changes in the dust streams from Jupiter, which take 1 - 2 months to reach Galileo.

A new capability for the Galileo orbital mission that was implemented early for SL-9 is on-chip mosaicing. This refers to the ability to make multiple exposures of the target *on* the CCD before copying to tape. The significant advantage of this capability over a single exposure per frame was that up to 64 Jupiter images (an 8x8 array resulting from 64 multiple exposures) could be stored for a tape space cost of one frame one exposure per frame would have limited us to the aforementioned 150 images making it virtually impossible to capture even a single impact because of the timing uncertainties. An example array of images is the one used to observe the W fragment impact shown in Figure 9. SS1 observing strategies varied over the six events it covered - for W, the platform was moved and an exposure shuttered every 2-1/3 seconds to provide images giving a time/ intensity history of the impact response.

Generally the observing strategy was for a single instrument to be prime for a given impact, and other instruments could ride along where practical. This was driven both by the need to limit the complexity of the sequences, as well as, the conflicting requirements of the different instruments; SS1 wanted to move in many small steps to build up the on-chip mosaic, NIMS wanted to sweep across Jupiter to

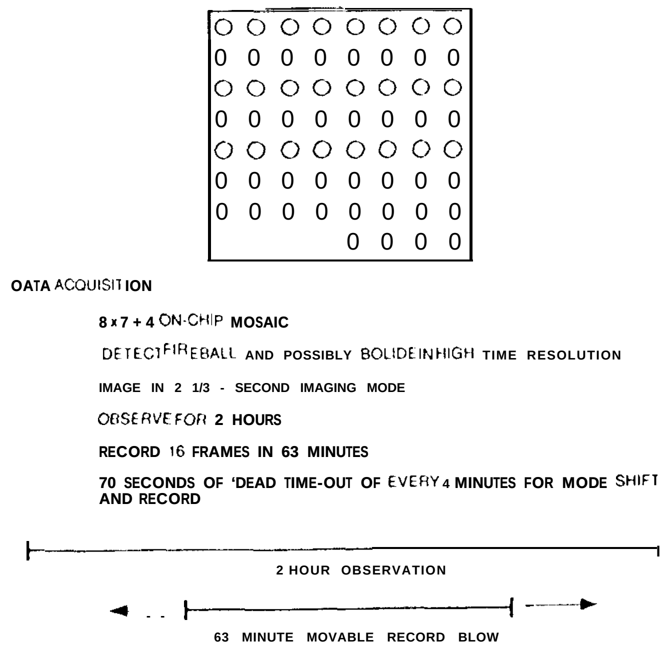


Figure 9. Fragment W 2 1/3 second OCM imaging

account for pointing inaccuracies, PPR wanted to point in a single fixed direction. For all but one observation, the approach used for the PPR data was to store the instrument data directly in the spacecraft central computer in a buffer that was then played to ground on a nearly daily basis. This was feasible because the PPR data output rate is relatively low, and had the advantage of providing a near real-time return for determining impact times. The utility of this in support of recorded data return was limited by the fact that the PPR was not observing the same impacts as were being recorded by the other instruments, An identical approach was used for the PWS, which observed continuously from before the first impact through the entire sequence. Again, a low data output rate made this feasible.

The sequencing strategy used for the recorded observations to solve the problem of changing impact time estimates was to design an observation window for each event of about two hours duration, during which the instrument would be pointed, operate, and take data. Then, a moveable record window of about one hour duration was placed in this observation window during which the data would be recorded. The shorter record window was necessary to avoid overflowing the tape, and since its placement could be updated quite easily late in the process, it provided the flexibility to respond to late changes in the impact time estimates. Figure 10 shows which fragment impacts were observed by which instruments and the approximate times of impact.

6.1 Preliminary Results

Data from the PWS and PPR that were buffered in the spacecraft computer have all been returned. Of the PPR observed events, nothing was seen on B, which is consistent with ground based reports that it was a weak event, a clear signal was seen for H and L, a faint signal was detected for Ql, and S was missed as a result of an out-of-tolerance shift in the time of impact from estimates during the development process. The H and L data are displayed in Fig. 11. After preliminary processing of the PWS data, no impact induced signals have been detected. This is not unexpected, since a'priori it was not thought highly likely that the impact response would generate signals that the PWS could detect. However, because of the uncertainty in what the response would be, and the considerable significance of a

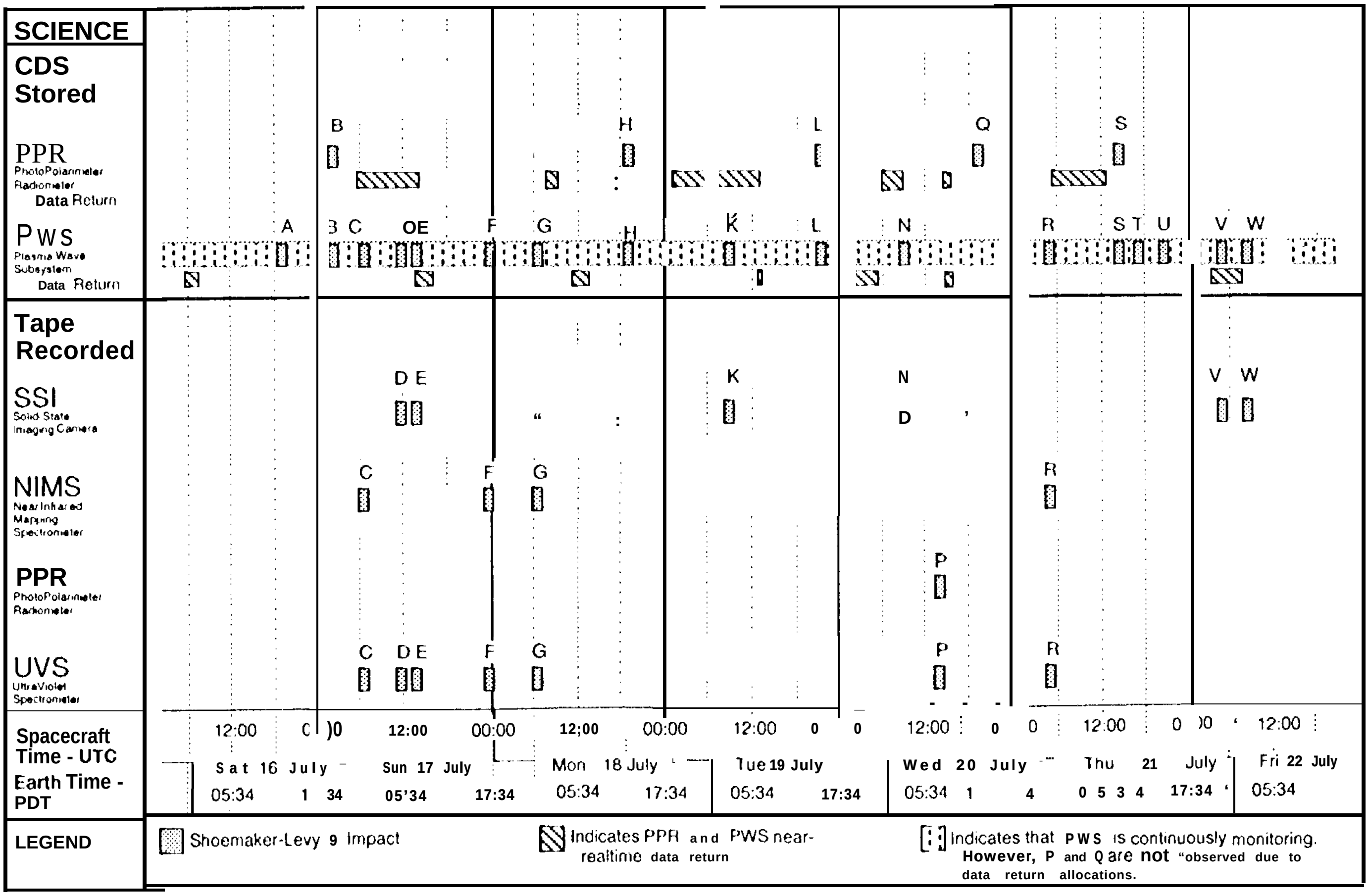


Figure 10. Galileo Shoemaker-Levy 9 Observation Plans

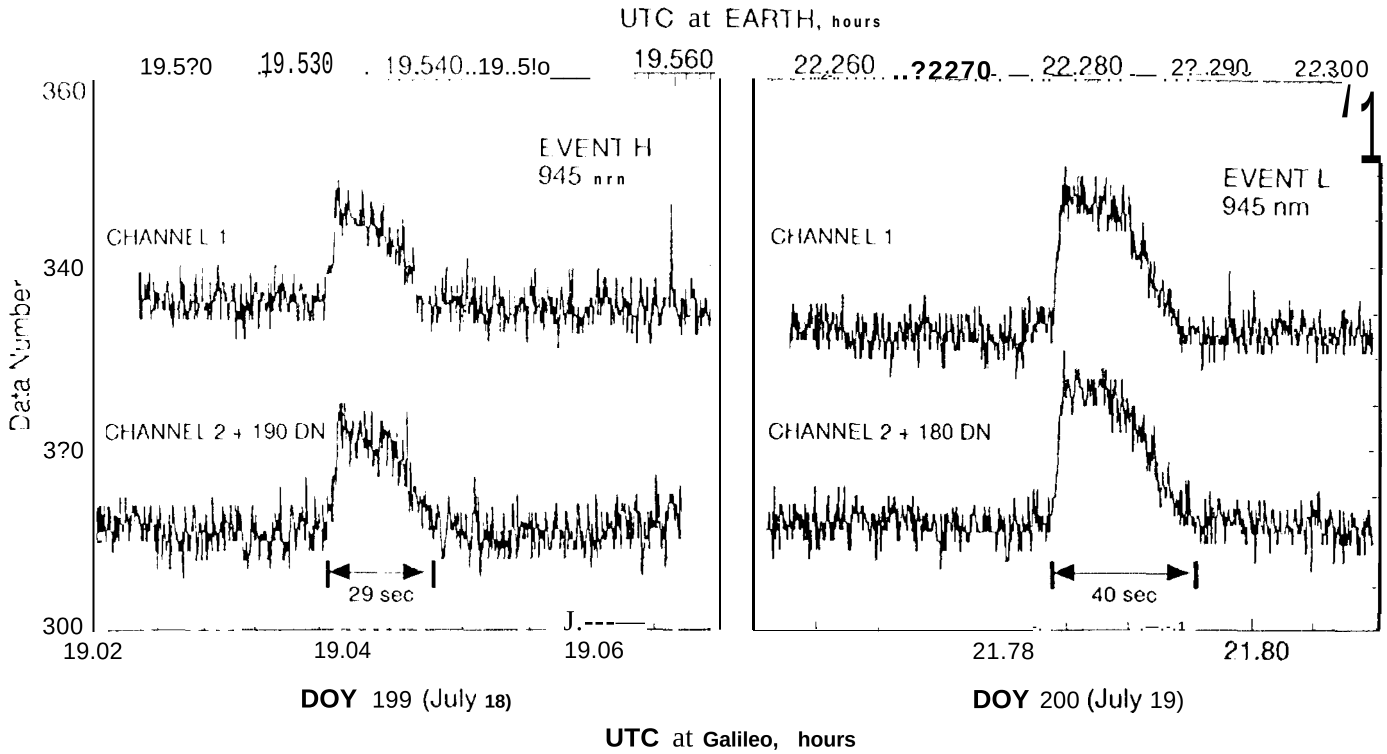


Figure 11. Galileo Photopolarimeter Radiometer Observation of Shoemaker-Levy 9 Fragment Impacts

response detectable by the PWS, the measurements were made. The recorded data returned to date have included pre-impact reference measurements from UVS and NIMS, small strips ("Jailbars") for the purpose of locating data on the tape for subsequent return, and a portion of the SSI frame containing the W fragment impact. Of the search data, NIMS has

Figure 12. Galileo SL-9 K Event

returned data on the G event that will provide the basis for limiting future G data playback to the portion of the scan containing Jupiter. SSI has very clearly seen the K event in its search data (Fig. **12**), and the W image return captured the impact as seen in Fig. 13. The PPR and SSI data indicate that the events observed produced near-infrared signals lasting a surprising 20 to 40 seconds with intensities ranging from ~1% of the total brightness of Jupiter (Q1 event) to over 10% (K event).

Playback searches for the purpose of locating the data of interest on the tape will be complete by late September, and from then through January of next year, the DSN tracking allocated to Galileo will be virtually dedicated to the return of the impact observations. The D and E observations *were* missed due to a modeling error in the ground software used to design the spacecraft sequence. Indications are that the balance of the Galileo observations were very successful, and will contribute new and unique information not available from the vantage point of Earth.

7. Arrival Preparations

7.1 Inflight (Computer) Load (IFL)

In calendar year 1995, virtually all spacecraft activity is dedicated to preparations for Jupiter arrival on December 7th. In February and March new Flight Software (FSW) will be loaded in the Com-

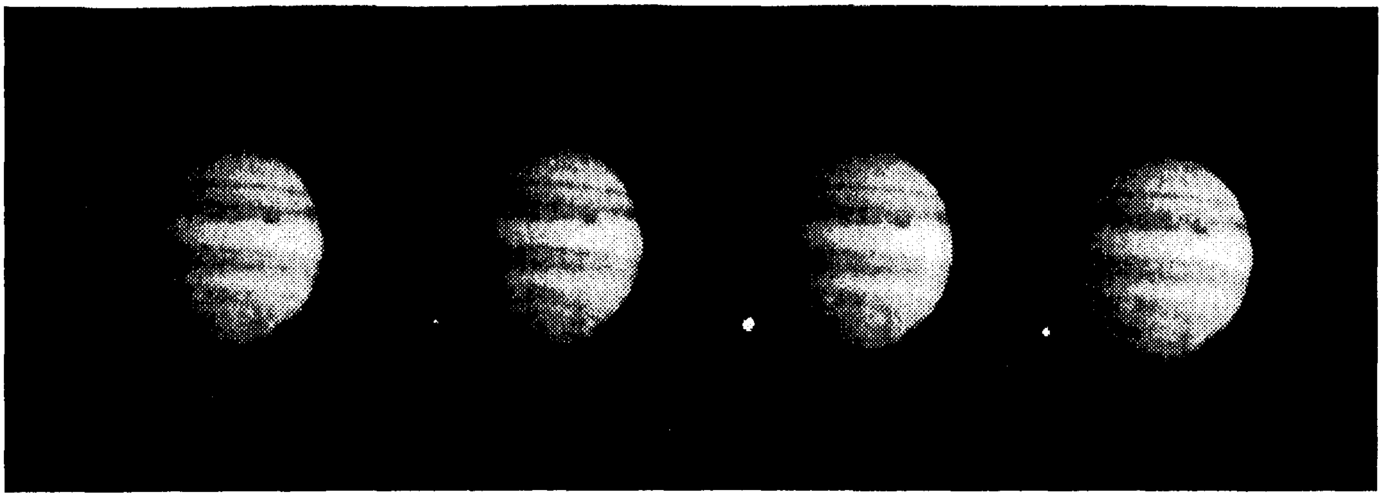


Figure 13. images of Jupiter at 2 1/3 sec intervals showing the night-side impact of fragment W of Comet Shoemaker-Levy 9

mand and Data Subsystem (CDS) and in the Attitude and Articulation Control Subsystem (AACS). While these augmentations represent a small percentage of total code, in both cases the total code must be recompiled and, consequently, both CDS and AACS will be completely re-loaded. Both subsystems have two redundant "halves" or strings. CDS nominally operates dual-string. AACS operates on one string only and switches autonomously to the other string if certain fault triggers trip.

Presently each side (string) of the CDS is divided into two equal parts: a primary and an extended memory - it's quad redundant in memory. The new FSW will first be loaded into the extended memory on one side while the primary memories on both sides operate the spacecraft dual-string in a quiescent mode. Then the loading side will switch operation to the new FSW in the extended memory and then copy its extended memory (the new FSW) into its primary memory. The second side will be loaded the same way such that the dual-string redundancy is maintained throughout the loading process. The primary purpose of the new CDS FSW is to store the highest priority Atmospheric Entry Probe data in the CDS extended memories. Originally, storing the Probe data on the tape recorder was the backup to the real-time transmission of that data to earth over the Orbiter HGA. Now, without the HGA, the tape recorder is the prime route and CDS extended memory storage is the backup. The tape recorder can be connected to only one string of the CDS at a time-- the new FSW adds a feature that will autonomously switch the recorder to the other string if the string to which it is connected goes down.

in August 1994, tests were performed that verified that every memory cell that has not been in regular use (a bit more than half the memory) is functional, thus providing high confidence that the entire CDS memory is fully functional. While now unlikely, there is an option to do additional memory testing before the loading in February.

In the case of AACS, only the off-line (i.e., the redundant, not operating) memory was tested in August. The memories must be swapped to test the currently on-line memory. Since the memories must be swapped to load the new FSW, the currently on-line memory will be tested in February before loading the new FSW when that memory is necessarily off-line for the loading. This avoided an unnecessary memory swap with its attendant difficulties and risks in August. The new AACS FSW will provide several layers of *new* fault protection for relay link antenna pointing. Nominally, the clock (azimuth) angle of the antenna will be controlled using the gyros. The star scanner is used to provide a gross check on the gyros and control is autonomously switched to the scanner if the miscompare tolerance is violated. There is considerable concern about the reliable operation of the star scanner deep in Jupiter's radiation field. Accordingly, the new FSW will obtain roll (clock) reference using only the brightest available star- Canopus- during relay. If Canopus is not being detected reliably, then the FSW will switch to the Sun Acquisition Sensor, which is not susceptible to radiation, and use the sun pulse for roll reference. These three sources of roll reference are progressively more robust but result in less accurate though quite adequate antenna azimuth control. Having three different reference sources provides maximum reliability for this most critical mission event.

7.2 Probe Checkout

The Galileo Atmospheric Entry Probe has been checked out several times in flight. A Systems Functional Test (SFT) was run on October 26, 1989 shortly after launch and again on December 4, 1990. A Mission Sequence Test (MST) was run on Earth-2 approach on November 21, 1992 when 28.8 kbps was available over the LGA. The SFT functionally tested all science instruments and engineering subsystems. The MST ran the entire pre-entry and descent mission sequence, except for irreversible events (e.g., staging), thus every unit received and executed the stored sequence commands as it will during the actual mission. In all tests, the Probe was found to be in excellent health. The only possible exception is that a radio signal amplitude measurement in one of the two redundant communication links indicates some unexpected variations, but the data is ambiguous and after thorough study it was determined that using both channels clearly provides maximum reliability. The Probe is powered by the Orbiter for all tests. The Probe internal power is provided by LiSO2 batteries which cannot be charged by the Orbiter and accordingly the Probe is never switched to internal power until just before release. An Abbreviated SFT (ASFT) compatible with the now 10bps Orbiter downlink was developed and demonstrated on Earth-2 approach on December 3, 1992. 'l'he ASFT tests for degraded batteries, pumps Argon out of the Neutral Mass Spectrometer (NMS) ionization chamber, and tests the Atmospheric Structure Instrument (ASI) accelerometers. The ASFT data will be used in determining if battery energy concerns warrant invoking the contingency mission. In the nominal mission a coast timer is powered at Probe release and clocks out the 150 days to Jupiter so as to "turn-on" the Probe and selected instruments to perform pre-entry science data gathering and buffered storage starling at entry --6 hrs to measure the portion of the innermost magnetosphere never reached by the Orbiter and to measure entry dynamics (e.g., acceleration, ablation, etc.). 'l'he coast and pre-entry consume about half the battery energy. If the indicated condition of the batteries warrants, the coast timer will not be powered, thus, abandoning the pre-entry science in order to conserve energy to maximize the descent science, i.e., maximum descent time before battery depletion. Of equal importance to the ASFT is the ground battery test. Three flight identical battery sets have been maintained since launch in ground facilities mimicking flight conditions. September 18, 1994, one of these sets began a 155-day coast and at the end of coast will "execute" the pre-entry science and descent mission. In November the other two sets will begin coast -- one with timer load; one without --- but stop before entry so as to be ready for anomaly investigation. These Flight Descent Antecedent Tests (FDAT) in conjunction with ASFT will be used to decide whether to opt for the contingency mission, in which the Probe and its instruments are not turned on until the entry g-switches trip and initiate the parachute deployment/aeroshell jettison staging sequence and descent mission. ASFT results will also be used to determine whether to switch the ASI primary accelerometer assignment.

The ASFT will be performed in March 1995 shortly after the IFL. The Probe telemetry during the ASFT will be stored on the Orbiter tape recorder and in the CDS using the new FSW. The verification of the new capability to store Probe data in the CDS will be provided by downlinking the data from the CDS storage, The taped data will also be downlinked. The contingency mission decision will be made by May 1st for input to the finalization of the Orbiter's Probe release flight sequence.

7.3 Probe Release

'l'he Orbiter is scheduled to release the Probe on July 13, 1995. The only command link to the Probe is through the umbilical cable; after the cable is cut it is impossible to command the Probe. Probe telemetry is available only through the Orbiter via the umbilical until cable cut and via the L-band Radio Relay Link after parachute deploy merit-- -there is absolutely no communication with the Probe during its 150 day free-flight to Jupiter.

The Probe is spin-stabilized at 10.5 rpm by spinning up the entire spacecraft to 10.5 rpm prior to release. There is no attitude or path control system on the Probe; it is totally ballistic. Thus, entry Flight Path Angle (FPA) and Angle-of-Attack (AOA) must be established by the Orbiter before release. TCM'S 23 and 24 (Fig. 1) will precisely adjust the spacecraft trajectory such that the separation impulse and all gravitational and non-gravitational (e.g., solar pressure, etc.) forces will result in an atmosphere relative Probe FPA of -8.6 deg (+/- 1.4 deg 99%) at 450 km altitude above the one-bar reference pressure surface.

At Release -6days, the Probe is switched to internal power. Probe data will be via the new CDS storage; it will also be tape recorded, but tape playback will be for contingencies only. Following verification of internal power and other checks, the umbilical cable is cut with a pyre-activated guillotine. Cable cut will be verified by the loss of Probe signals to the Orbiter.

After verification of umbilical cut, the spacecraft will turn to the required Probe Release attitude, transition from dual-spin to all-spin mode, and then spin-up to 10.5 rpm. All pre-release actions that can be performed before the turn are done then because the telemetry link performance is less at the release attitude because earth will be 10 deg off the LGA axis. The Probe is released by simultaneous firing of the three (captured) explosive nuts at the "tripod" attach points. Each nut has redundant pyres. The separation springs impart a 0.3 m/s AV to the Probe. The Probe release attitude is parallel to what will be the atmosphere relative entry velocity vector, i.e., zero A-0-A. The predicted aggregate affects of turn accuracy and separation and all subsequent disturbances shows that the 6.0 deg A-0-A tolerance specification is easily met. At key points throughout the sequence, "go commands" must be received from the ground for the sequence to continue. After Probe release, the Orbiter spins back down, transitions to dual-spin, and turns back to near earth point.

7.4 Orbiter Deflection Maneuver (ODM)

Seven clays after Probe Release the ODM is performed to target the Orbiter to its 10 flyby aim point which establishes the Orbiter trajectory for all arrival events. The required Probe entry time is derived from the Io flyby time such that the desired Relay Link over flight geometry is achieved—entry time is controlled by the pre-release TCM's described earlier.

ODM will be a 59.6 m/see maneuver, 29 deg off earthline. It will be the first use of the 400N main engine. In a manner entirely analogous to the Probe Release scenario, the Orbiter must turn to the maneuver attitude and then spin-up to 10.5 rpm to provide stability for the 400N burn. The ODM could be performed with the ION thrusters with a net Propellant Margin penalty of only 3 kg. However, using the 400N engine for ODM provides a crucial inflight characterization of the engine well prior to its mandatory use for Jupiter Orbit Insertion (JO]). To the maximum practical extent the planned JOI operating conditions (pressures, temperatures, etc.) will be duplicated at ODM and the observed engine performance will be analyzed to determine any changes to the JOI plan. The 400N engine burns are terminated on accumulated accelerometer counts with min/max timed backup cutoff. The thrust level inferred at ODM is, for example, an important consideration in the min/max "timer" setting for JOI.

'l'he 400N engine uses the same propellant supply (MMH&NTO) and feed system as the 10N thrusters. The feed system pressurization gas (He) is also used to actuate the 400N engine propellant valve via an electrically operated pilot valve. Nominally, the last pyro event on Galileo is opening an isolation valve to flow the He pressurant to the pilot valve. 'l'his will occur a few days after Probe Release in preparation for ODM. On each of the redundant 10N thruster branches a pair of electrically operated latch valves secures the propellant supply from the thrusters except during their intended *use;* likewise, there is a pair on the 400N branch. In a contingency *where* a ***400N*** latch valve does not open, pyro isolation valves will be fired open to manifold a ION propellant branch to the ***400N*** branch, below the latch valves. The 400N ODM will demonstrate with high confidence that the engine and feed system are working properly or it will indicate contingencies must be invoked for JOI.

7.5. Jupiter Approach and Arrival Science Observation Plan

'I'he approach of the Galileo Orbiter to Jupiter from its interplanetary trajectory will provide a number of science data gathering opportunities which are unique in the Galileo mission. Starting about two months out, a global color image of an approximately half-lit Jupiter will be taken. Only in the vicinity of apojove on the first orbit in the satellite tour will the spacecraft again be far enough from Jupiter that Jupiter can be contained within the field of view of the camera, and that at a much larger solar phase angle - hence much less of the disk illuminated. The initial perijove passage at 4 R_J - the next lowest in the tour is at 9 R_J - provides the only close encounter with Io and the only passage through the 10 torus and the inner magnetosphere. Also, because the inclination of the approach trajectory relative to the plane of the orbits of the satellites is nearly 6 deg, approaching from below the plane, a near south polar pass of Europa at about 34,000 km range will provide the only opportunity for global coverage of the south polar region of Europa. Once in orbit, the first two encounters with Ganymede serve to reduce the orbital inclination to - zero in order to be able to transfer from one satellite to another in the tour - hence no distant polar passes are feasible, And finally, observations of the probe entry site relatively close to the time of entry can only be made during this part of the mission.

7.5.1 *Data Return*

The majority of the science data gathered on approach and through the encounter period will not be returned until several months later as a consequence of the relatively low telemetry rates available and other priority activities, primarily the return of the Probe data and loading of the new flight software necessary to accomplish the orbital part of the mission. In fact, the only Orbiter science data returned in the approach and encounter phases of the mission will be the three-filter approach global image of Jupiter and the continuing instrument Memory Readouts (MROs) of the Magnetometer (MAG), the Dust Detector (1)1) S), and the Extreme Ultra-Violet spectrometer (EUV). 'l'he rest of the down link telemetry capability in the approach phase is used to return data in support of optical navigation required to achieve the delivery to Io, and engineering telemetry for monitoring spacecraft performance during this critical phase of the mission, All the remainder of the data to be gathered will be stored on the tape recorder and returned to Earth starting in the late spring of 1996 [Ref. 1). Consequently, the limiting resource is not the downlink data rate, but rather the space available on the recorder for data storage. Of the four tracks on the recorder, with a total capacity of 900 Mbits, three tracks are devoted to recording observations up through Io closest approach plus about thirty minutes, following which the single remaining track will record low rate science (LRS) including 1,200 bps engineering telemetry through completion of the orbit insertion burn and most importantly, the Probe relay data exclusively during its 75-minute descent mission.

7.5.2 *Observing Plan*

Figures 14, 15, and 16 show schematically the observations planned in this period, Each of the eleven science instruments on the Orbiter, plus radio science, will be actively participating in this phase of the mission. Figure 14 indicates the planned data gathering activities on a scale of days, starting about two months out, into about two days out. 'l'he first activity is taking the Jupiter approach global image, which has been timed so that the Probe entry site (albeit -60 days before entry), as well as, Ganymede and 10 will be in view. Starting at about this same time, instrument MROS, which are being done throughout most of interplanetary cruise, are performed with an increasing frequency ranging from once per week to once per day, with one ***34*** hr period, where the bow shock of the magnetosphere is expected to be found, containing 5 MROs. The first two of four UVS radiation monitoring events are also performed in this period. These observations are primarily for the purpose of measuring the radiation background in support of future observation designs, and not for science per se at this time. All of the science data gathered in this period will be returned before the Jupiter encounter except the UVS radiaion monitoring, which is recorded. Figure 15 covers the last two days before encounter, and describes activities up to when the spacecraft crosses the orbit of Europa about eight hours before perijove. One key scientific focus in this period is observing the Probe entry site in order to provide a calibration and correlation between these remote sensing observations and the subsequent in-situ measurements made by the Probe during its descent. 'l'he entry site is in view about every 9.8 hours, Jupiter's rotation rate, so the approximately 20 hour period shown provides three opportunities for entry site viewing. During this period, the UVS, the SS1, the NIMS, and the PPR are making multiple observations as shown. The end of this observing period eleven hours out is the last opportunity to view the entry site, since one Jupiter rotation later is when the Probe entry and data relay occur, ant] all the Orbiter resources are dedicated to insuring maximum reliability for this critical event. The SS1 is the most active instrument in the time period covered in Fig. 15, with activities including three 10 monitoring events and one full disk Io color image, a mosaic of the south polar region of Europa, and images of two of the smaller non-Galilean satellites of Jupiter, Thebe and Adrastea.

'l'he PPR instrument will be making observations of the two points in the atmosphere that will subsequently (about a day later) be measured by the radio signal at the entrance to and exit from the occultation of Earth by Jupiter. The PPR observations are made at approximately the time when the points are at the sub-spacecraft point *on* Jupiter, and will serve to provide a remote sensing measurement to correlate with the radio signal in-situ measurement. PPR will also, jointly with NIMS, do a south polar region mosaic of Europa.

Figure **16** shows the activities in the period from about the time of the Europa passage up to the Io closest approach time plus about 30 minutes, at which time all remote sensing activity is terminated, and the Orbiter completes the final preparation for receiving the Probe data and performing the orbit insertion burn required to be placed in orbit about Jupiter. The one exception to this is that the scan platform will be left in an attitude after all 10 data gathering is complete such that the PPR field of view will drift across the Probe entry site just prior to Probe entry for one last measurement, with its data output being recorded. Fields and particles instruments are gathering data for recording from about the time of the Europa orbit crossing through the entire encounter period and out to about the range of 10's orbit crossing on the outgoing leg of the orbit. Gaps in this recording occur during the Probe relay, during tape repositioning for beginning the final record period, and during record rate changes required by the remote sensing instruments.

There are six fields and particles instruments: MAG, DDS, Plasma (} '1 S), Plasma Wave (PWS), Energetic Particles Detector (EPD), and Heavy Ion Counter (HIC). This period of the mission is of special priority for investigators associated with these instruments because it is the only time in the mission that the Orbiter will penetrate this deeply into the inner magnetosphere, passing through and inside of the 10 torus. Radiation dose limits preclude additional passes at these low altitudes later in the mission. Figure 17 shows the path of the Orbiter as it passes through the torus. The ordinate is z-height measured from the centrifugal magnetic field equator, which "wobbles" relative to Jupiter's rotational

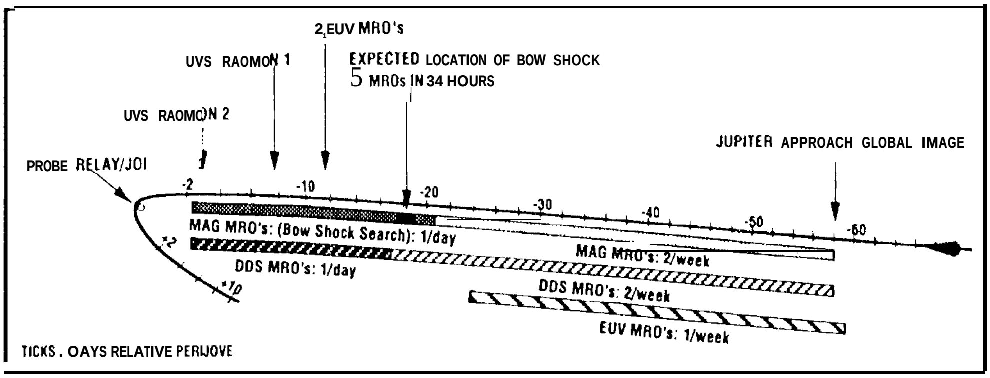


Figure **14.** *Jupiter Approach Science Plan: -60 to –2 days*

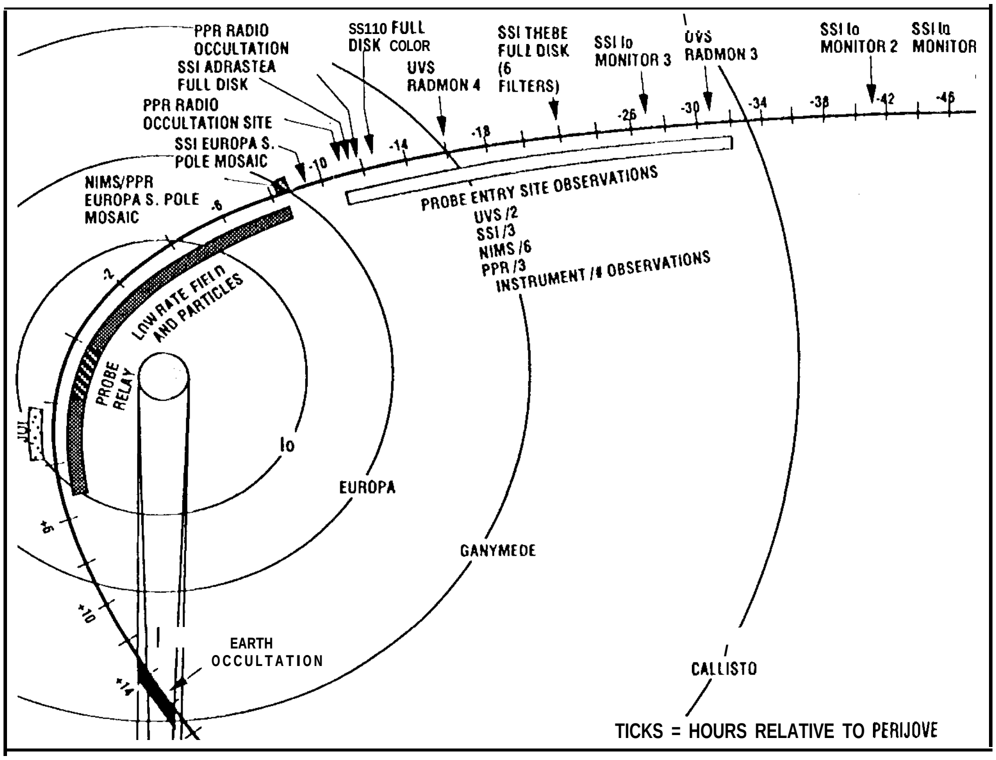


Figure **15.** *Jupiter Approach Science Plan: -2 days to Europa*

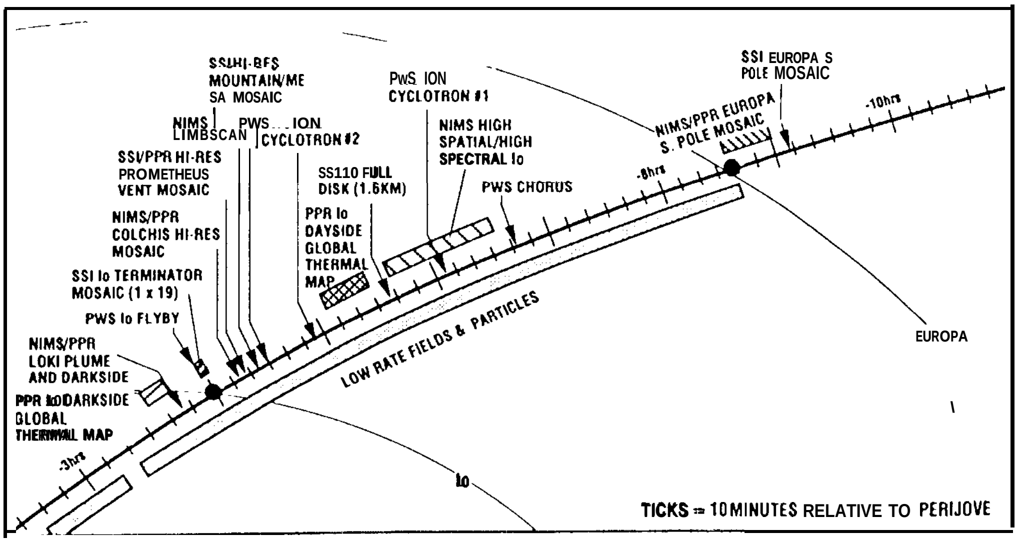


Figure 16. Jupiter Approach Science Plan: Europa to Io

equator, thus, the appearance of non-planar motion. Achieving a torus path as ideally placed as this one was a key factor in the selection of the arrival date at Jupiter.

The remote sensing instruments are focused almost exclusively on 10 in this final period, including both global and specific feature observations. Specific targets include 10 limb observations and measurements of volcanoes discovered by Voyager and monitored by ground based observations, including Loki, Prometheus, and Colchis.

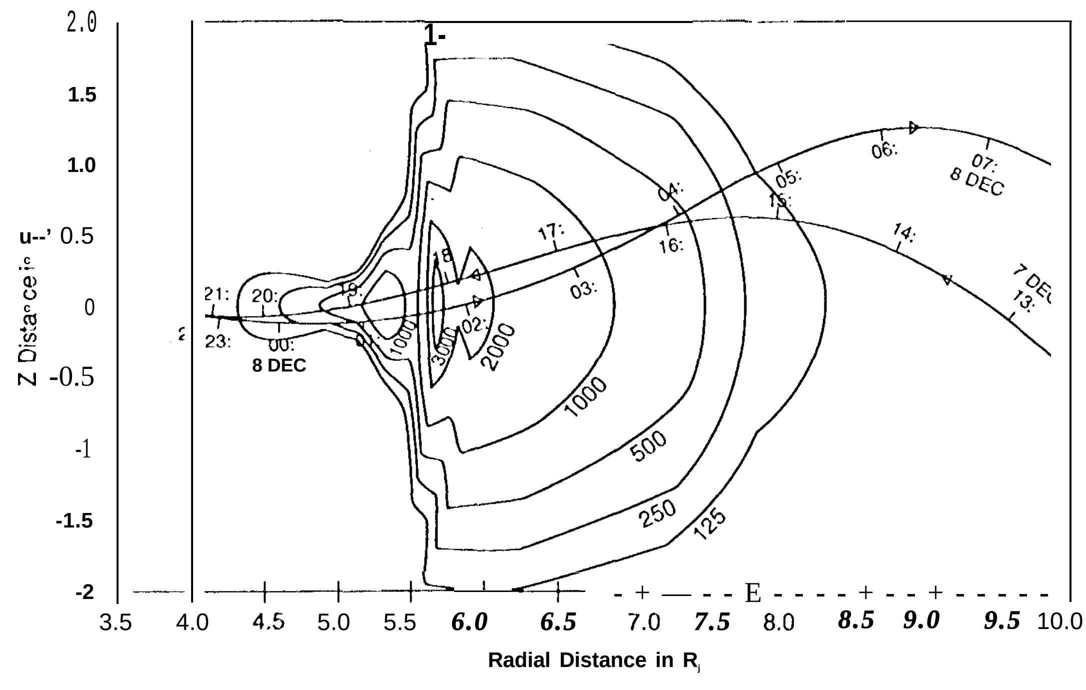
When the recording of both engineering and science data has ended following the orbit insertion burn, the tape recorder is completely filled. The Probe data are returned first and will be played back in early '96. Following this, in the vicinity of apojove of the first orbit, a propulsive maneuver is performed to raise periapsis to -10 R_J to limit subsequent radiation exposure. Next comes a series of engineering activities in preparation for the orbital mission, including the loading of the orbital phase flight software. 'l'hen, the Jupiter encounter data are returned to Earth using the newly installed capabilities, beginning in May of '96 and continuing till the first encounter with Ganymede in July of '96.

7.6. Relay/JOI: Critical Sequence Design and Contingency Planning

7.6.1 *Overview and Background*

The preceding section described the science sequencing being developed for this period. Critical engineering events for Relay and Jupiter Orbit Insertion (JOI) start at approximately Probe entry -21 days when the CDS is commanded to critical engineering mode and the critical sequence is started. At entry ***-9.5*** days, fault protection reconfiguration begins and the Relay Receiver (RRH) oscillators are turned on. At entry -3.5 days, spacecraft safing and RPM overpressure algorithms are disabled. At entry -16 hours, RRH-1 is turned on; RRH-2 is turned on later at entry -3.5 hours. 10 closest approach occurs at entry -4.3 hours.

Science sequencing will stop at entry -3.6 hours after which the Orbiter will be configured into the Relay Readiness Configuration (RRC). The reconfiguration for the relay is complete by entry -3.4 hours. After the 75-minute relay data acquisition is complete, reconfiguration for JOI is accomplished over the following 65 minutes. Reconfiguration in-



TIME TICKS ARE 1 HOUR APART, IN UTC SCET.

CONTOURS ARE OF ELECTRON DENSITY (AS e^-/cm^3), AS PREDICTED BY THE MODEL (ELECTRONS ARE JUST ONE COMPONENT OF THE 10 TORUS)

AS MODELED HERE, THE 10 TORUS HAS LONGITUDINAL SYMMETRY ABOUT THE JOVIAN CENTRIFUGAL AXIS, WHICH IS TILTED 6.4° FROM THF JOVIAN ROTATIONAL AXIS - HENCE THE LARGE VARIATION IN Z ALONG GALILEO'S TRAJECTORY. Z = 0 REPRESENTS THE CENTRIFUGAL EQUATOR.

Figure 17. 10 *Torus Passage*

cludes stowing the relay antenna (RRA) and spinning up to 10,5 RPM. After JOI is complete, the spacecraft will be returned to 3 RPM dual-spin cruise mode.

The probe relay data acquisition and JOI critical mission activities are in fact "time" critical, i.e., the events must occur at specific absolute UTC times. The time critical nature of these activities and the i]nport.ante of fault tolerance result in unique requirements on both the sequence design and the fault protection flight software design.

For all other non-critical mission phases, the spacecraft sequence is terminated and the fault protection design safes the spacecraft and waits for ground to respond. During the critical sequence phase, the critical events will continue to be executed in the event of hard or transient faults and the spacecraft fault protection design will autonomously reconfigure the spacecraft subsystems to the required states. The remote sensing and fields and particles observations (non-critical) executing during this phase will be terminated in the event of a serious fault to prevent undesirable interactions with the execution of the fault protection response algorithms and the critical events. Because of the high level of spacecraft sequencing activity and the many operational state/configuration changes needed, it is important that the autonomous fault protection always be configured properly to respond to faults as the spacecraft state sequentially transitions through the Relay/JOI activities.

The need to have the critical events continue and the non-critical activities terminate in the event of a fault results in the requirement for a stand alone critical engineering Relay/JOI sequence to be built and exhaustively tested and analyzed for nominal and fault conditions. The approach and encounter science sequences are designed to run concurrently with the critical sequence.

The Jupiter environment during the Relay/JOI will be the harshest to which the spacecraft will ever be exposed. Though the spacecraft has many design features to "harden" it to the SEU/radiation/ESD environments, there is no guarantee that the spacecraft will perform anomaly free. The critical sequence must accommodate transient events (SEUs, CDS bus resets, AACS PORS) to the maximum extent feasible.

7.6.2 *Project Preparation Activities for Relay/ JOI Readiness*

Activities planned to maximize the reliability of completing the critical events include the following:

]. Critical Sequence Design and Development
2. Sequence Validation (Test & Analysis)
3. Spacecraft In-Flight Tests
4. Relay/JOI Contingency Planning
5. Relay/JOI Ground Demo (Spacecraft Test Bed)
6. Facility, GDS, and Flight Team Support Planning
7. Flight Team Test & Training

Activities 1 through 4 are the subject of the rest of this paper.

7.6.3 *Critical Sequence Design and Development*

The development and test of the Relay/JOI sequence was deferred to post-launch for the 1989 launch mission. The baseline sequence was developed and tested for the 1986 launch mission. A database of Relay/JOI action items has been maintained since 1986 to the present. The critical sequence development process started formally in August 1993. Key elements of the process include: (1) special sequence working group; (2) a Project Office level steering group; (3) three iterations of the sequence with allowance for a contingency iteration following Probe release and the first use of the 400N engine; (4) validation of each iteration including spacecraft test bed testing using the new Phase 1 (Ref. 1) Flight Software and analysis; (5) special peer design reviews and walk-throughs of nominal and fault scenarios.

'l'here are unique requirements on the development of the critical sequence. The most significant requirements are summarized below:

1. Events are time critical and must occur at specific absolute times.
2. Sequence shall be single-point failure tolerant— no single spacecraft fault shall prevent Relay/ JOI.
3. Transient faults shall be accommodated, e.g, CDS bus resets, radiation environment effects, sequencing errors (in the non-critical science sequence).
4. 'l'he sequence shall complete the critical events and keep the spacecraft safe even if the non-critical science sequence fails to execute.
5 'l'he science sequence shall be terminated in the event of faults.
6. The critical events shall not depend on the star scanner operation in the high radiation environment.
7. Critical sequence restart points shall be accommodated-- used in the event a CDS string goes down due to a transient or external fault. The CDS string and the sequence could then be restarted by contingency ground commands and reinstate dual string operations.

8. Configure the spacecraft for Probe relay as soon as possible following the Io encounter science and constrain spacecraft activities to those required for critical events.
9. The sequence shall be designed with simplicity and reliability at the expense of performance, if necessary.
10. Always maintain a command and telemetry RF link and maintain spacecraft health and safety under nominal and fault cases.

The December 7, 1995 arrival date, the HGA deployment failure, and the post-launch action item resolution all result in significant changes to the 1986 baseline sequence. The major changes required are summarized below:

1. New arrival date/event times.
2. Start the critical sequence at Probe entry -21 days (previously -10 days) to reduce risk relative to commanding problems.
3. Accommodate 10N thruster pulsed-mode only operation for the 10 RPM spin-up/down for JOI. The AACS 12.0 flight software uplinked in February '93 included this pulsed-mode capability and it was demonstrated in March '93.
4. Accommodate the uncertainty in the star scanner operation in the high radiation environment. Retesting of the star scanner in the expected Jovian environment has identified a significant risk to the successful acquisition of the three star set available at the Relay/JOI spacecraft inertial attitude. As a result of this and the need to have a robust source of clock angle reference onboard in order to point the relay antenna, new AACS flight software capabilities are included in AACS 13.0. The new software allows AACS operation with a single star (Can opus is observable) or with the Acquisition Sensor sun pulses in the fault case when both the gyros and star scanner are not functioning reliably.
5. Accommodate the use of the LGA instead of the HGA and maximize the telecom link margins. The critical events occur near conjunction at a solar separation angle of 9 degrees and at near maximum telecommunication range. A data rate of8 bps will be used prior to Io through the critical events. in addition, a fully suppressed carrier downlink enabled by the new DSN Block V receivers will improve telemetry performance .
6. Accommodate a significant reduction in the available spacecraft power. Power available for spacecraft operations is 40 watts less for the LGA S-Band high power transmitter operation versus the HGA baseline X-Band low power operation anticipated at launch. The power consumption is higher than for other mission phases since the RRH receivers are turned on for the relay. A steady-state power margin of -40 watts is required. Solving this problem has been a very challenging and analysis-intensive. Solutions include violating hardware temperature "flight rules" while still maintaining hardware safety and performing significant heater cycling.
7. Update the RRA pointing profile during the 75-minute Probe relay to minimize the number of slews while maintaining sufficient relay link margin for the first 40 minutes (a depth of 10 bar is a primary objective). The results of this analysis concluded that four repositions during the relay (75-minute) and initially pointing 5 degrees ahead of the Probe maximizes prospects of success.
8. Establish the spacecraft inertial attitude for relay and JOI prior to the start of the critical sequence and include no turns in the critical sequence. The attitude selected was a trade off of many factors including telecom, propellant, the acquisition sensor off sun requirement (5 degrees), scan platform pointing performance, etc. (See Fig. 18).
9. Accommodate the storing in CDS extended memory of the Probe relay symbol data. This capability was included in CDS 9.5 flight software to provide redundancy in acquiring the relay data; DMS fault would have been a single point failure (Ref. 1).

The CDS will be put in critical engineering mode prior to the start of the sequence. In this mode the CDS will roll back the sequence to the previous "MARK" and resume execution in the event of a CDS fault response. The critical sequence will be execut-

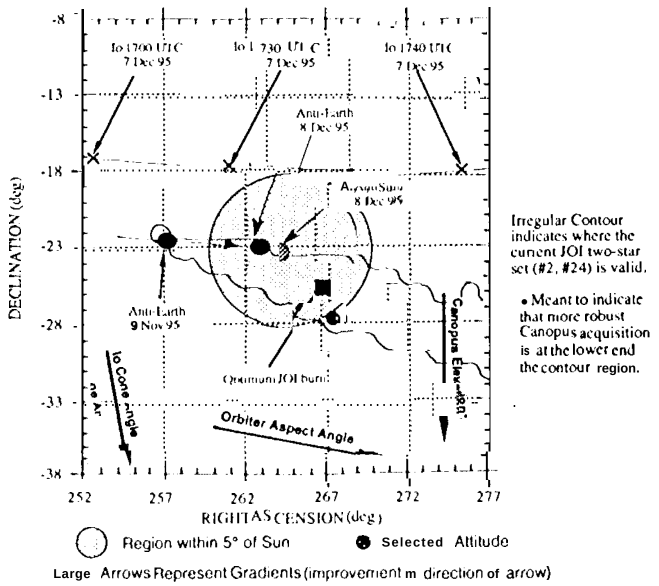


Figure 18. Relay Attitude Considerations

ing in parallel out of both CDS strings. Redundant commanding on each CDS string is included for reliability and to remove single point failure vulnerabilities. 'I'he current status is that the second iteration of the sequence development has been completed and is well along in test.

7.6.4 *Sequence Validation (Test and Analysis)*

An extensive test program will be conducted on the spacecraft Test Bed. Testing includes both nominal and numerous fault cases. The spacecraft Test Bed facility includes flight spare hardware or engineering models and associated support equipment for the CDS, AACS, DMS (tape recorder), and the SS1, A power subsystem simulator is also included in this facility. The CDS, AACS, and SS1 flight software is loaded on the facility for testing.

A summary of the fault cases that will be tested are listed in 'l'able 1. In addition to the fault case testing, nominal testing will include execution of the concurrent science sequence for the high activity period starting at approximately 10-3 hours through JOI spin-down.

Since the Test Bed is limited in validating the sequence relative to some constraints and attributes, analysis is also utilized. Examples of items that will be validated by analysis include the RRA pointing profile, power margin, hardware thermal limits and, in general, sensitivity analysis for performance variations. Analysis will also be done on additional fault scenarios not included in the test program-–the intent is to test or analyze all branches of the fault responses in each phase of the sequence. One successful mechanism for the analysis is conducting peer group walk-throughs of nominal and fault scenarios. This mechanism has knowledgeable subsystem experts in a meeting atmosphere walk through the sequence and spacecraft response event by event.

7.6.5 *Spacecraft In-Flight Tests*

One of the requirements on the critical engineering events is that none aretobe first-time events. The required engineering functions are, therefore, required to be demonstrated on the spacecraft early enough such that, if a problem exists, it can be resolved prior to the critical sequence. The required

Table 1. Fault Cases to be Tested

	Relay	Spin-up/down	JOI
AACS Power On Reset (POR)*	X	X	X
Undervoltage Recovery	X	X	X
Thruster sticks open during spin-up		X	
Accelerometers data not available			X
Accelerometers cut-off burn too early			X
CDS Bus Reset	X	X	X
Multiple CDS Bus Resets occuring in succession, first on the prime string, then on the secondary string.	X	X	X
Acquisition Sensor Attitude Estimator operation, initiated by SEQID not going to output phase & Gyro failure, and followed by AACS POR	X		
CDS non-privileged error; CDS Effectual down	X		
Multiple Fault Protection routines running at once (Acid Test)		X	
Gyro failures with/without Canopus available	X		
SBA hardware failures with/without Canopus available	X		
SAS hardware failure with/witl~out Canopus available	X		
Spin Detector failure		X	
Prime CDS string-down/swap DMS	X		

*POR stands for Power on Reset, which would restart the AACS processor in the event of an undervoltage condition, I/O/Memory/CPU hardwares swaps.

spacecraft in-flight tests or demonstrations are listed below. Some of the activities have already been successfully demonstrated.

1. RRA positioning and slew test (Completed May 1993)
2. 10 RPM spin-up/down (Completed March 1993)
3. Probe data symbol capture and storage (Probe checkout March 1995)
4. One star SEQID/Acquisition Sensor Attitude Estimator operation at the relay off-sun attitude (April 1995)
5. Europa/Io scan platform slew test (August 1995)
6. 400N engine operation (ODM - July 1995)

The purpose of the RRA slew test was to demonstrate the actuator operation (dual drive motors) and to verify and calibrate the potentiometers relative to cone position and slew rate characteristics. The calibration results are used in the critical sequence to position the antenna.

The 10.5 RPM spin rate is required for Probe release and the 400N maneuvers. The in-flight test demonstrated the capability, uncovered a configuration modeling error, and satisfied all requirements, e.g., wobble magnitude limits for Probe release.

Probe data symbol capture and storage is a new capability providing redundancy in the relay data collection and was included in the CDS 9.5 delivery. Since the test facility does not include the Probe or RRHs, an in-flight demonstration is deemed necessary, The capability will be demonstrated as part of the! planned Probe checkout.

The one star SEQID/ASAE operation is a new capability added to AACS 13.0 flight software. It is essential for Probe relay antenna pointing in the event there is a gyro failure or if the gyros are autonomously turned off due to various AACS faults. The test will be conducted at the same off-sun angle as during Relay/JOI.

The Europa/Io scan platform slew test will be conducted after the Probe is released and the RRA positioned for the relay. The purpose of the testis to insure that performing the remote sensing sequence prior to the critical engineering events will not result in a fault or anomalous behavior. Performing the identical sequence on the spacecraft is the highest fidelity verification technique. The unresolved Ida anomaly where the gyros were autonomously turned off particularly motivates this spacecraft test.

The 400N engine will be used for the first time to perform the ODM after probe release. Performance characteristic will be obtained which could be reflected in the JOI burn parameters if warranted. If the main engine valve fails open with the first use, there is a backup configuration for JOI which uses the latch valves to start and stop the burn.

Capturing the Probe relay data and achieving Jupiter orbit are the highest priority mission objectives. The Relay/JOI critical engineering sequence and the on board fault protection are being implemented in the most reliable way to accomplish Relay/JOI under both nominal and fault conditions.

7.6.6 *Relay/JOI Contingency Planning*

Relay/JOI contingency command actions must be available for transmission in the event that unexpected/unplanned spacecraft conditions are observed. These conditions/states may be due to untimely failures or anomalies induced by the harsh Jovian environment. The one-way light time (signal) at Relay/JOI is 52 minutes. The Relay/JOI critical engineering sequence is designed formaximurn reliability and contains all commands necessary to complete Relay/JOI without ground action.

During the 21-day critical sequence period, several other sequence memory loads will be transmitted to perform navigation approach maneuvers, to initialize spacecraft states and perform the Jupiter inbound Europa/Io science encounters. The Europa/Io science sequence is scheduled to be transmitted about 3 days before Relay/JOI after the completion of the final approach TCM activities. It is noted that prior to the Joad of the Relay/JO] critical engineering sequence, other spacecraft activities will be executed from the J_{AA} and J_{AB} approach stored sequences transmitted in early October and November 1995, respectively. These sequences include Jupiter approach maneuvers to be performed from mid-to-late November '95. Also included in these stored sequences are several engineering calibration and health maintenance activities. Because many of these activities are enabling for a successful Relay/JOI, contingency planning must consider the Jupiter approach phase as well as the "immediate" Relay/JOI period. Contingency planning covering the period from early October '95 up to the latest establishment of the Relay Readiness Configuration (RRC) at about 2.75 hours before Relay/JOI is discussed below.

Contingency Planning Scoping

Contingency planning consumes significant Flight Team resources. It is vitally important to establish what anomalies will and will not be considered for contingency action and to what degree contingency actions should be developed. To scope the effort, some fundamental questions focusing on diagnostic data and risk management-related issues were addressed. For example:

1. What diagnostic data is available?
2. What commands might be transmitted?

3. What commands should be transmitted?
4. How should the response strategy change the closer the spacecraft gets to Relay/JOI?
5. What is the latest time before Relay/JOI that a CDS string recovery from a transient bus reset should be attempted?
6. What is the latest time before Relay/JOI that any command be transmitted?
7. What should be the sequence recovery strategy?
8. What testing should be performed prior to command transmission?
9. Could commands interfere with the Relay/JO] sequence or cause an unintended result?

Contingency Planning Requirement / Guidelines

To do effective contingency planning, a clear set of requirements and guidelines is needed. The planning requirements and guidelines assume that the Relay/JOI critical engineering sequence is "bulletproof', contains no latent errors, and has successfully completed intensive testing under spacecraft nominal and faulted conditions. Based on the aforementioned fundamental questions and assumptions, the following preliminary contingency planning requirements and guidelines have been established:

1. The benefit of contingency action shall substantially exceed the risk of no action.
2. Action shall be essential for successful completion of Relay/JOI.
3. Action shall not interfere with the Relay/JOI sequence.
4. All contingency actions shall be tested with the Relay/JOI sequence prior to transmission.
5. in case of reasonable doubt, no contingency action shall be taken.
6. There shall be adequate time to respond to unintended contingency action response.
7. A complete set of predicted measurement values shall be available and verified by test.
8. Unexpected measurement values shall be unambiguous and present for at least two consecutive samples or independently verifiable by the measurements.
9. Unexpected measurement values shall be outside of the pre-determined acceptable range.
10. Unexpected measurement values/anomalies shall be duplicated by test with measurement signatures and responses identical with observed flight data.

Preliminary Fault Scenarios

Currently, a preliminary list of credible fault/anomaly scenarios has been generated. The list includes entry into SAFING for new anomalies, a recurrence of the CDS transient bus reset, relay receiver- related failures, data mode and relay antenna pointing state incompatibilities for Relay/JOI, and vulnerabilities associated with planned disabled fault protection. The contingency response for a fault/anomaly will depend on when it occurs and what it is. For instance, the response may be different if a fault/anomaly occurred days or weeks before Relay/JOI compared to just hours. Contingency response may also be different if the fault/anomaly was a new first-time observed event rather than a recurrence of a previously observed one,

As previously mentioned, the Jupiter approach activities and the Europa/Io science collection activities are all important. Because of this, contingency planning must also consider stored sequence recovery capability.

Sequence Recovery

The general guideline for sequence recovery is to restart in time so that the next planned uplink sequence can be loaded before the time it is to go active. Specifically, should a spacecraft fault/anomaly terminate the Europa/Io concurrent science sequence days before Europa, a truncated science sequence will be considered for transmission. Should a spacecraft fault/anomaly terminate the sequence during one of the three approach optical navigation image activities, recovery will be planned to capture at least one image. Finally, should a spacecraft fault/anomaly terminate the sequence during or just prior to an approach maneuver, the spacecraft must be properly configured and commanded to complete two of the three planned approach maneuvers. Clearly, required engineering health maintenance must be performed; it is envisioned that these activities would be accomplished using special utility command actions.

Additional Contingency Planning Actions

In addition to sequence recovery capability, contingency planning will include CDS string recovery from a transient bus reset and the restarting of the Relay/JOI critical engineering sequence in that string. Having both CDS strings available for Relay/JOI provides sequence execution redundancy and improves the prospects of a successful Relay/JO]. Because recovery from a transient bus reset has been estimated to take about 15 hours assuming all goes well, the latest time prior to Relay/JOI that a recovery may be attempted is about 24 hours.

Other faults/anomalies have been identified and analysis for contingency planning is in process. Generally, the preliminary assessment is that the number of contingency command actions will be small because the spacecraft is equipped with substantial redundancy and fault protection to autonomously detect and respond to faults. All the spacecraft functions essential for Relay/JOI completion are preserved by on board fault protection.

The final set of contingency planning scenarios for Relay/JOI is scheduled for completion in early 1995. It will then be decided what faults/anomalies will be covered by contingency plans.

8. Summary

Project Galileo has had another very good year. Spacecraft performance continued to be excellent. The largest propulsive maneuver ever required of the ION thrusters targeted Galileo directly to Jupiter for the first time. Virtually all high priority Ida science data was returned from the tape recorder with a tremendous unexpected bonus–- the discovery of the first known asteroid satellite. Galileo captured the only direct observations of Comet Shoemaker-Levy 9 crashing into Jupiter.

The development of the new flight software and ground capabilities to perform the mission on the Low-Gain Antenna is on schedule; overall performance of the new system will very likely exceed original expectations. The Project is now focused on preparing for Jupiter arrival. In particular, the emphasis is on making the onboard autonomous fault protection as robust as possible for Relay/JOI – the most critical events of the entire mission, which necessarily occur in the harshest radiation environment.

9. Acknowledgment

Project Galileo represents the work of thousands of people. They all deserve acknowledgement for the many accomplishments of Galileo to date and for the tremendous promise it holds at Jupiter.

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